The current-driven anomalous transports in multi-fluid and kinetic plasma descriptions: A simulation study of anomalous transport levels

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Abstract

The generation of anomalous transport in collisionless plasma is a significant issue in many energetic plasma environments, such as in the solar flares or in the strong toroidal currents of magnetic confiment device that applies Joule heating as one of the major heating mechanisms.

In most fluid models the generation mechanism and the magnetide of anomalous transport are usually treated as auxiliary terms external to the model description and are free to manipulate, the anomalous transport is indeed a noticeably self-generated effect exhibited in a multi-fluid system. The generation mechanism of current-driven anomalous transport in a multi-fluid system is studied via a one-dimensional three-fluid simulation. Similar to the current reduction in kinetic Vlasov simulation, this three-fluid simulation shows that the localized electrostatic structures appear at the nonlinear stage of plasma-wave development. These large-amplitude structures appeared in both simulations play a role as obstcles for electron bulk drifts, causing a resistive effect in the view that currents are reduced.

Comparing the current relaxation levels with kinetic Vlasov simulation of the same initial setups, it's found that there is a higher anomalous transport in the multi-fluid plasma, i.e. a stronger current reduction in the multi-fluid simulation than in the kinetic Vlasov simulation for the same setup. To isolate the mechanism that causes the different anomalous transport levels, we hence investigated the detailed wave-particle interaction by using spectrum analysis of the generated waves, combined with a spatial-averaged distributions at different instants. It shows that the Landau damping in kinetic simulation takes a role that stablizes the plasma-drifting system, when the bulk veliocity of electron drifts drop beneath the phase velocity of waves. The current relaxation process stops while the relative drift velocity between electrons is still high.

On the other hand, the current-driven anomalous transport in a multi-fluid system is stabilized only when the relative drifts were reduced to a very small value, when the system is stable in the linear dispersion analysis. This explains the generation of stronger anomalous transport in a multi-fluid system than in a kinetic plasma. In the beam return-current setup used here, we found the ability of current relaxation in multi-fluid model is around 3.5 times stronger than in kinetic model. With the recognition that the Vlasov description is the more detailed and physical description for the reality, any external dissipation term used in multi-fluid models to stablize system should be able to bridge these differences. However, beside this simplified 1D electrostatic case it is necessary to examine this effect in a 2- or 3-dimensional electromagnetic system in the view that more instabilities and extra degrees of freedom might change the nature of anomalous transport.

Keywords: Anomalous Transport; Multi-fluid Plasma; Plasma Heating

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I. INTRODUCTION

Anomalous resistivity is an influential and critical factor for many energetic plasma phenomena in collisionless plasma environments. One of the examples that is influenced by Anomalous resistivity is the magnetic reconnection prior to the solar falres, which is a process that the topology of the magnetic field lines in a current sheet changes and converts the magnetic field energy into the kinetic energy of reconnection outflow. Anomalous resistivity also plays an dominant role in the solar flare spectrum evolution of plasma distribution [2] and in the MeV electron transport characteristics of the laser beam interaction with the ambient overdense plasma [3].

The causes of anomalous resistivity are usually studied via the comparison with the generation mechanisms of the classical collisional resistivity. From the kinetic point of view the collisional electrical resistivity is described by classical binary collisions between charge particles, in which the mean-free-path is the key factor that determines the collisional probability within a certain time. Nevertheless, in most of the space plasma environments the temporal scale of classical binary collision is usually much longer than the characteristic period of energetic phenomena, therefore the binary collision is not sufficient to account for the occurrences of these transient events. In addition, the mean-free-path of binary collision is usually larger than the scale length of the spatial structures , e.g. the collisional mean-free-path of coronal plasma is around $1AU$ but the scale length of a typical solar flare loop is of the order $10 - 500Mm$, which is much shorter than the explainable value. Without the classical binary collisions, different species in plasma can exchange their energy and momentum through the wave-particle interaction with the generated electrostatic or electromagnetic waves in the system. The bulk motion of charged particles can be slowed down after the interaction with those phase space structures, for which the effect is identified as anomalous resistivity.

According to Boltzmann's H-theorem, collisions always push distribution function toward the Maxwellian state to maintain a thermal equlibrium. For collisionless plasmas, instead of binary collisions, wave-particle interactions take over the role as a momentum converter that draws the system toward equlibrium. In a multi-fluid system, each plasma species is described by a set of parameters, such as drift velocity, temperature and density. In principle the system comprised of several species, such as a multi-fluid system, is deviated from equlibrium, hence a specific mechanism is expected to draw the system back to the stable equilibrium state. With the bulk drift motion of charged particles, e.g. electrons in a current system, the distribution function is deviated from Maxwellian and the system is considered as free-energy supplied.

Multi-fluid plasma model has the advantage over a kinetic model on saving numerical resource, and more importantly a multi-fluid model conserves more informations of wave interactions with plasma, as a fluid. Therefore multi-fluid model has been applied to many studies of energetic plasma phenomena. For the plasma transport between terrestrial magne-

tosphere and ionosphere (M-I coupling) in the appearance of field-aligned current is studied via three-dimensional two-fluid (H_+, e) model [4]. Ajustable external diffusion terms (D_f) are introduced to continuity and momentum equations to stabilize the system. In the study of flash-like magnetic reconnection in astrophysical plasma, a three-dimensional multi-fluid model is also applied to the possible magnetic reconnection in the dusty proto-Solar nebula [5]. In addition to the external-superposed collisional frequiencies between charge particles and neutral dust in continuity and momentum equations, anomalous resistivity is also assumed in the induction equation as functions of: (1) the spatial location referred to the center of current sheet, and (2) the relative drift between ions and neutral dusts. Plasma transport takes place in those models, even without the external adjustable anomalous terms. In general two collisionless transport effects are included, the self-generated anomalous transport and the artificially-added anomalous coefficients in continuity and momentum equations.

Although an external anomalous transport term, either assumed in a form of resistivity or collision frequency, the detailed informations of physical interaction between waves and particles, as well as the weight on the above mentioned transport effects, are absent in the multi-fluid model. An ambiguity therefore arose for dispute: with the manipulation of anomalous resistivity the simulated transport process do have physical correspondences or they are simply the concessions of parameter adjustments?

Unlike the incomplete description of wave-particle interactions in multi-fluid models, the detailed processes of plasma evolution in the velocity space is expressed in fully kinetic model. For turbulence and transport in large magnetic-fusion-relevant tokamaks, a systematic nonlinear gyrokinetic simulation study of the scalings and parameter dependences is carried on the ion-thermal transport rates in the work [6], and the geometry with strong sheared magnetic field is considered in [7]. A 5D gyrokinetic simulation of plasma turbulence in a toroidal configuration with experimentally relevant parameters is performed in [8]. The nonlocal heat transport by the high energy tail electrons is found to be essential for the preheating in laser fusion under high intensity laser irradiation [9] Also, for the study of transport characteristics in laser fusion a three-dimensional Particle-In-Cell simulation describing the interaction and anomalous transport of an intense laser beam with a plasma slab is presented in [10].

Despite these different plasma descriptions used for the anomalous transport studies, in principle the momentum or energy transports between waves and plasma are due to the analogy collisions between charged particles with the localized electrostatic structures via electric or electromagnetic forces in the collisionless environments. Current driven instabilities, such as Buneman mode or various acoustic instabilities, start to develop in the system. Those localized electrostatic structures can start to grow from a small perturbation, like from the plasma thermal perturbation, and those electrostatic structures can slow down the charged particles by taking their kinetic momentum and convert into the wave energy, in the way like the classical binary collision.

With the knowledge of plasma transport in collisionless environment, anomalous resis-

tivity can be determined via the momentum conversion rate. Anomalous resistivity is a macroscopic quantity that is defined as the current reduction in collisionless plasma. According to this definition the anomalous resistivity has been widely studied and discussed in fully kinetic simulations such as kinetic Vlasov simulation [12, 13] with open boundary or via PIC simulation [14] on electrostatic double layer formation in one dimensional case. In the fluid descriptions of plasmas, such as in resistive MHD [15] or even in 3D multi-fluid simulation [16], the anomalous resistivity is usually defined as a free parameter and the generation mechanism is not concerned. The localized phase-space electrostatic structures are the clear exhibitions of charge separation and particle trapping effects, and a multifluid model includes only the charge separation term while keeping the distribution function of each species a Maxwellian state.

In principle a multi-fluid model can exhibit, to a certain level, the anomalous resistivity effect, i.e. the anomalous resistivity can be self-generated. The external anomalous transport or dissipation terms are mainly used to stabilize the system. However, to remove the ambiguity and dispute that what is the actual level the external anomalous should be applied in a multi-fluid model, a detailed comparison of the generated plasma transport in fully kinetic and multi-fluid models with the same background setup should be carried.

In this paper we aim to study the anomalous resistivity generated by the charge separation effect in a three-fluid plasma. Starting from the simplest electrostatic case, the nolinear evolution of current carring system and the generated collisionless transport is examined. In order to compare the multi-fluid results with fully kinetic simulation, we assumed a beam return-current system with background ions, and this setup can be an analogy to the drifting plasmas propagating in solar coronal loop during solar flare. The linear stability of the beam return-current system is presented in section II. In section III a kinetic Vlasov simulation is performed and the spectrum analysis is carried out for the generated waves. To compare the anomalous transport generated in a multi-fluid plasma, simulation is carried for the same initial setup in section IV. Physical explanation of the difference on current relaxation levels in two simulations is provided in section V and a summary is given in discussion.

II. DISPERSION ANALYSIS

A beam return-current system is commonly seen in many environments, e.g. in the solar flare X-ray loops, in the terrestrial cusp region during magnetic substorm [17] and in the laser fusion experiment [18]. Usually, a beam return-current system is composed of two counter-streaming electron beams with one ion species stationary in the background. One of the electron beams which of same temperature as background ions is induced by the generated magnetic field, from the external injected beam.

In beam return-current system we assume current and charge-neutrality conditions, i.e.

$$\sum_\alpha q_\alpha N_\alpha = 0 \qquad \sum_\alpha q_\alpha N_\alpha V_{d\alpha} = 0 \tag{1}$$
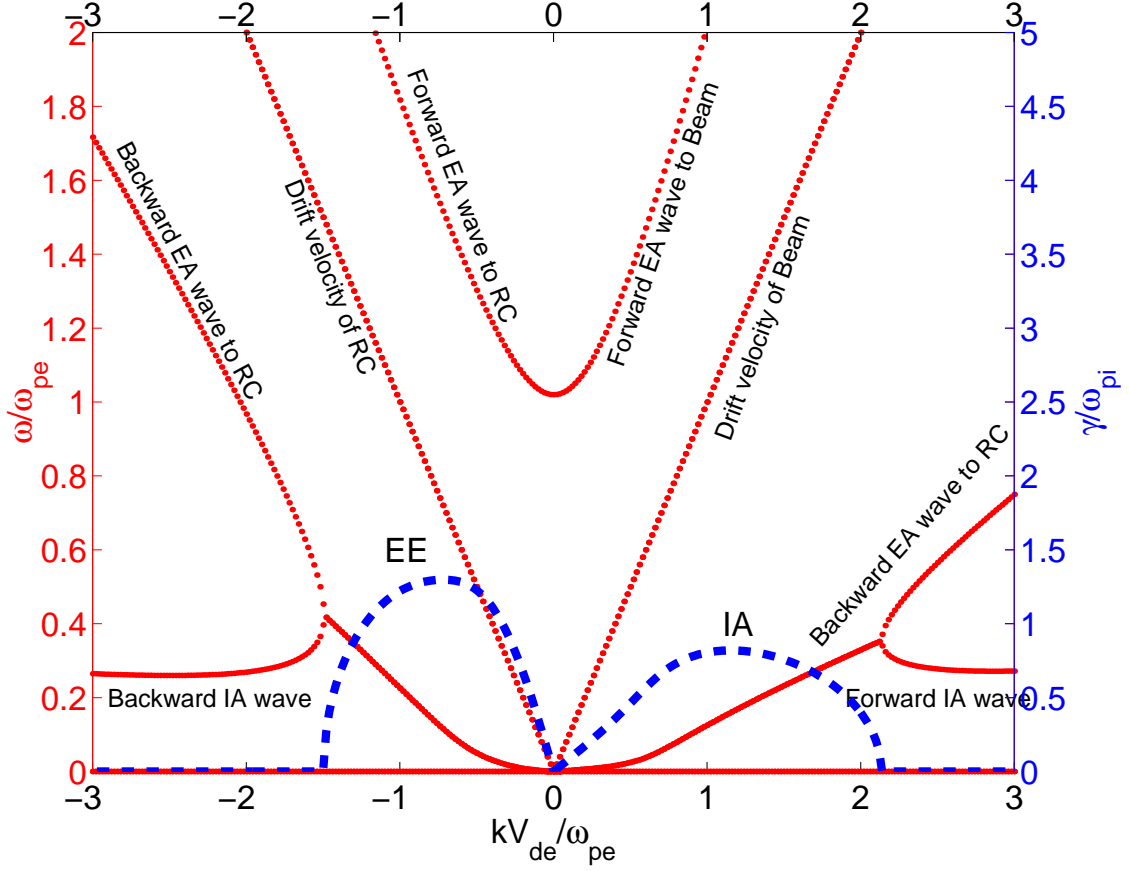
FIG. 1: The linear multi-fluid dispersion analysis of the current-driven instability in a beam return current system. Two electrostatic modes, the forward propagating ion acoustic instability and the backward propagating electron acoustic instability, are excited in the environment.

where N_α represents the densities of beams, $V_{d\alpha}$ and $v_{t\alpha}$ are the bulk velocity and thermal velocity of species α. In this one dimensional multi-fluid system, the electrostatic condition $(\vec{b} = (c/\omega)\vec{k} \times \delta\vec{E} = 0)$ is also assumed for the reason that large amplitude electrostatic waves have dominant influence on anomalous momentum transports in collisionless plasma. This electrostatic assumption indicates $\vec{k} \parallel \vec{E}$, i.e. the electric field perturbation is logitudinal to wave vector.

The electrostatic dispersion relation for beam return-current system is:

$$1 = \frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{p,Beam}^2}{(\omega_{*Beam}^2 - k^2 S_{Beam}^2)} + \frac{\omega_{p,RC}^2}{(\omega_{*RC}^2 - k^2 S_{RC}^2)} \tag{2}$$

The Buneman mode [19] is a fundamental fluid-like instability in beam-plasma system (or ion-acoustic mode, IA, if thermal correction is considered). Also, in a beam return-current system the existence of two electron populations and their relative drift can excite an two-stream electron-acoustic (EE) instability [20].
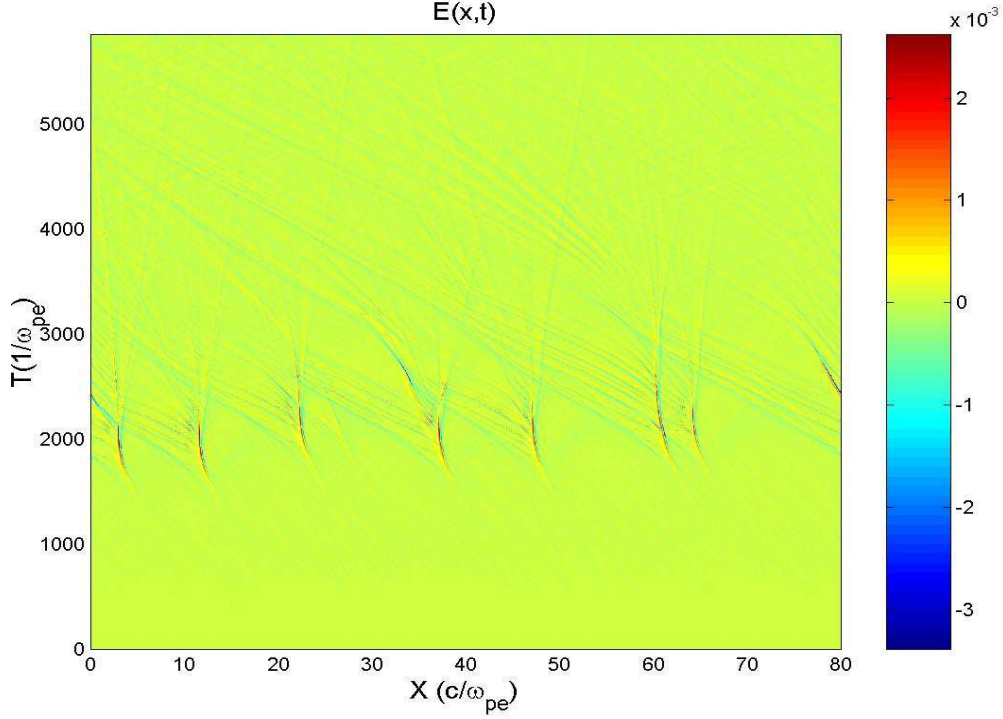
FIG. 2: The electric field history $E_x(x,t)$ from fully kinetic Vlasov simulation. At the nonlinear stage of instability development, there are several solitary-like double layers appeared.

For isothermal beam and return-current $(T_{e,Beam}/T_{e,Plasma} \approx 1)$, ion-acoustic mode is excited along the return-current direction and an EE two-stream instability in the beam direction. These two electrostatic instabilities are the two fundamental modes in the beam return-current system. The instability dispersion analysis of the system is shown in fig.1, and for which the flow direction of electron beam is along the positive axis while the return-current electron is along negative axis.

III.   KINETIC ANOMALOUS TRANSPORT FROM VLASOV SIMULATION

In collisionless plasma the momentum transport among species is via wave-particle interaction, which is simply a manifestation of particle resonance with waves of close phase velocity or vice versa. In kinetic description, physics ranging from small scale particle motion to large scale plasma collective motion is included in the the Vlasov equation.

For the electrostatic case considered here, i.e. in the nonrelativistic zero-magnetic field limit, the Vlasov-Poisson equation for sepcies α is

$$\frac{\partial f_\alpha}{\partial t} + \vec{v} \cdot \frac{\partial f_\alpha}{\partial \vec{x}} + \frac{q_\alpha \vec{E}}{m_\alpha} \cdot \frac{\partial f_\alpha}{\partial \vec{v}} = 0 \tag{3}$$

7

The above equation neglects the binary collision term. The absence of classic collision indicates that, in the higher moment expressions of the Vlasov equation, the momentum and energy conversion between species is via wave-particle interactions.

To study the momentum and energy dissipation of beams, a 1-dimensional periodic boundary condition is applied. The simulation domain is set $X = [-40c/\omega_{pe}, 40c/\omega_{pe}]$, which is an intermediate length between kinetic and fluid scales. The velocity ratios between two drifting electron and one background ion species is as following:

$$V_{d,Beam} = -V_{d,RC} = 2V_{th,RC} \tag{4}$$
$$V_{th,Beam} = 2V_{th,RC} = 2V_{th,ion}$$
$$N_{RC} = N_{Beam} = N_{ion}/2$$

where $V_{d,Beam}$ and $V_{d,RC}$ are the bulk drift velocities of beam electron and return-current electron; $V_{th,Beam}$, $V_{th,RC}$ and $V_{th,ion}$ are thermal velocities of beam electron, return-current electron and background ion. The reference velocity here is $V_{th,RC} = 0.01C$. In this simulation the mass ratio between electron and ion is chosen $m_i/m_e = 25$.

This fully-kinetic simulation with the above set of parameters is run for a sufficient time $T = 5800\omega_{pe}^{-1}$. The electric field generated in this simulation is shown in a temporal-spatial coordinates in fig.2. Localized electric field structures formed and developed at some locations. Those structures gradually developed into large amplitude electrostatic structures that can hinder the bulk motion of electron drifts at time $T = 1600\omega_{pe}^{-1}$. As discussed in previous literature [2] these structures are called electrostatic double layers (DLs) and they play the role as energy converters. The whole energy conversion process can simply catagorized at three stages: (1) The bulk drifting motion drive the growth of local electric field perturbations (2) The kinetic energy of bulk drifting motion is accumulated and transformed into wave energy (3) The localized large-amplitude electric field structures (DLs) dissipate and convert wave energy into plasma thermal energy.

Current histories of beam electron and return-current electron are shown in fig.3. In this figure it exhibits the relaxation of electron bulk motions, at the late stage of simulation, is about 3/4 of the initial value. This value, however, is quite constant for the same velocity ratio as used in eq.4. The other run, which is not shown here but used a reference velocity $V_{th,RC} = 0.1C$ exhibits similar relaxation level.

Take a 2nd moment on equation 3 a fluid momentum equation for species α is obtained, which depicts the the individual contributions of momentum transfer in a collisionless plasma.

$$m_\alpha n_\alpha \frac{\partial v_\alpha}{\partial t} + m_\alpha n_\alpha v_\alpha \frac{\partial v_\alpha}{\partial x} + \frac{\partial P_\alpha}{\partial x} + en_\alpha <E_x> = 0 \tag{5}$$

The first two terms indicate the momentum transport from the inertia of species α, following the flow velocity; the third term $(\partial P_\alpha)/(\partial x)$ is the momentum transport from
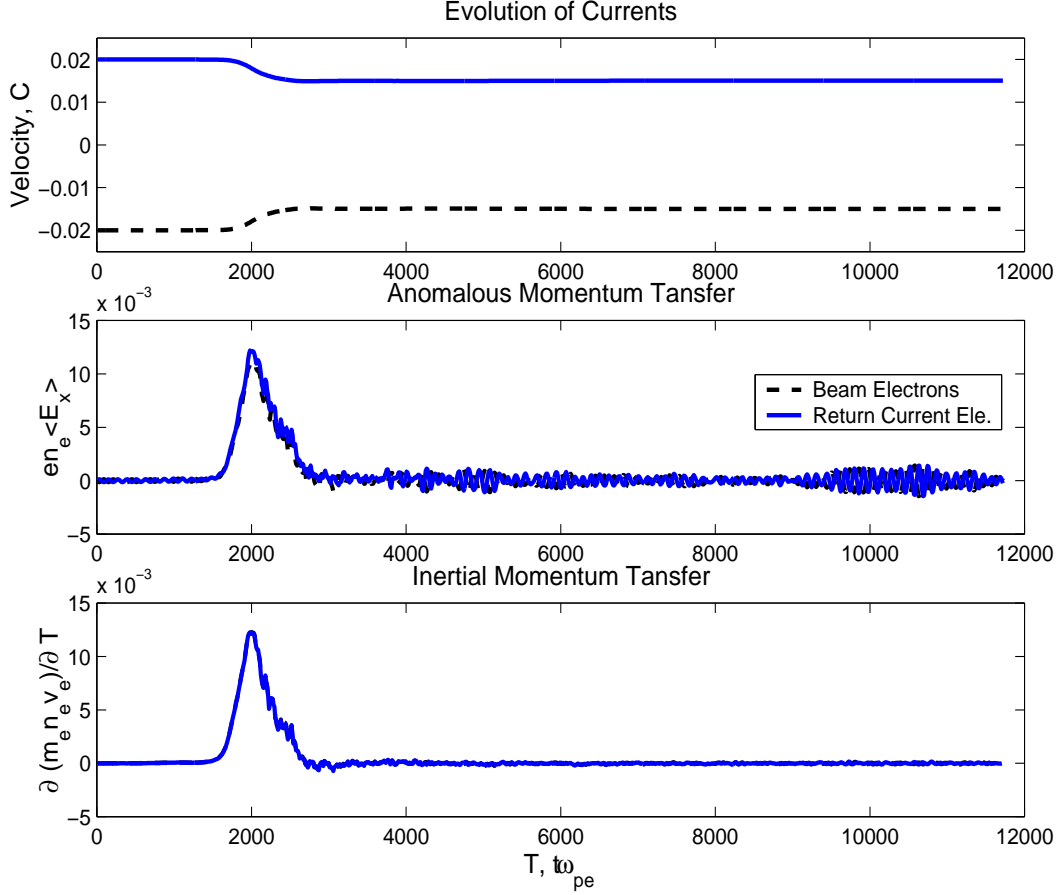
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FIG. 3: The temporal evolutions of electron bulk motions from Vlasov simulation. The bulk velocities of electrons reduce to 3/4 of the original values and the dissipation of bulk kinetic energy correspond to the appearance of electrostatic double layers, indicating that those structures play a role as energy converters. The second and third panels are the individual contributions of momentum transport in this simulation, as discussed in eq.7

pressure gradient and the forth term is the "anomalous" momentum transport from the localized electric field structures.

These individual contributions of momentum transport in a streaming plasma with an open boundary condition are well studied in [1]. In a simulaton domain with an open boundary the pressure and bulk velocity of species α, the second and third terms in eq.5 are different on two ends, therefore they contribute to the momentum transport. In our study of comparing anomalous transports from fully-kinetic and multi-fluid plasma descriptions, a periodic boundary is applied

$$\frac{\partial < m_\alpha n_\alpha v_\alpha >}{\partial t} + \frac{m_\alpha n_\alpha v_\alpha^2|_{v_{\alpha,2}}^{v_{\alpha,1}}}{\bar{X}} + \frac{P_\alpha|_{P_{\alpha,2}}^{P_{\alpha,1}}}{\bar{X}} + e < n_\alpha E_x >= 0 \tag{6}$$

The subscript 1 and 2 indicate the values at the right and left boundaries.

The calculated pressures and bulk velocities on two ends are equal in a periodic boundary,

hence the second and third terms are zeros in eq.6, i.e. the momentum transport in whole simulation domain is fully due to the anomalous term.

$$\frac{\partial < m_\alpha n_\alpha v_\alpha >}{\partial t} = -e < n_\alpha E_x > \tag{7}$$

In fig.3 the momentum transport from inertial and anomalous terms are plotted in the second and third panels. The agreement of these two trends shows the momentum transport in this system is primarily from wave-particle interactions.

With the information of localized electric field, another factor that is important for momentum transfer via wave-particle interaction is the spectrum of the generated waves. To study the characteristics of waves in the system, a spectrum analysis is applied and it demonstrates the wave intensity in the $[\omega, k]$ space. The spectrum at different instants is shown in fig.4. It is clear the strongest initial electric field perturbations travel at velocity $V_{ph} = -0.01C$ along the return-current direction. When the DLs appear in the instability growing phase $T = 2343\omega_{pe}^{-1}$ the spectrum splits into very low phase velocity and high phase velocity regions, which correspond to the velocities of DLs and fast electron holes [2]. After the wave energy is further converted into plasma thermal energy, most of the electric field structures travel at the velocity of fast electron holes $V_{ph} = -0.02C$, indicating a post-instability stage.

IV. SELF-GENERATED ANOMALOUS TRANSPORT IN MULTI-FLUID PLASMA AND THE PHASE SPACE ANALOGY

In this free-energy supplied multi-fluid plasma, system is usually stable and plasma waves are generated if there is small perturbation. To mimic the thermal fluctuation in a warm plasma condition, spatially random perturbation is imposed on background plasma density, and the initial fluctuation level is set to be $1/10^{11}$ of the background value, which is set to avoid the imposition of further unstable waves. To preserve the initial charge and current neutrality condition, the enhancement of beam electron density corresponding a depletion of return current electron density on the same location of simulation domain.

Comparing with Vlasov simulation, in order to isolate the key mechanism that causes the anomalous transport difference among many possible effects, the same initial and boundary conditions are applied in the three-fluid simulation.

Similar to our understanding of anomalous transport generation in kinetic simulation, the plasma bulk motion is strongly influenced by the localized electric fields. Hence to study the relationships between electric field perturbation and other physical quantities, the history of electron bulk motions, the temporal evolution of the electric field wave-power and the effective anomalous transports $R_j = (dI_j/dt)/I_j$ are depicted in figure 5, where $I_j = m_j n_j v_j$. In the first panel, the current history of electron beam and return-current start to decrease at around $T = 650\omega_{pe}^{-1}$ and it takes about $T_{span} = 2000\omega_{pe}^{-1}$ to reach the
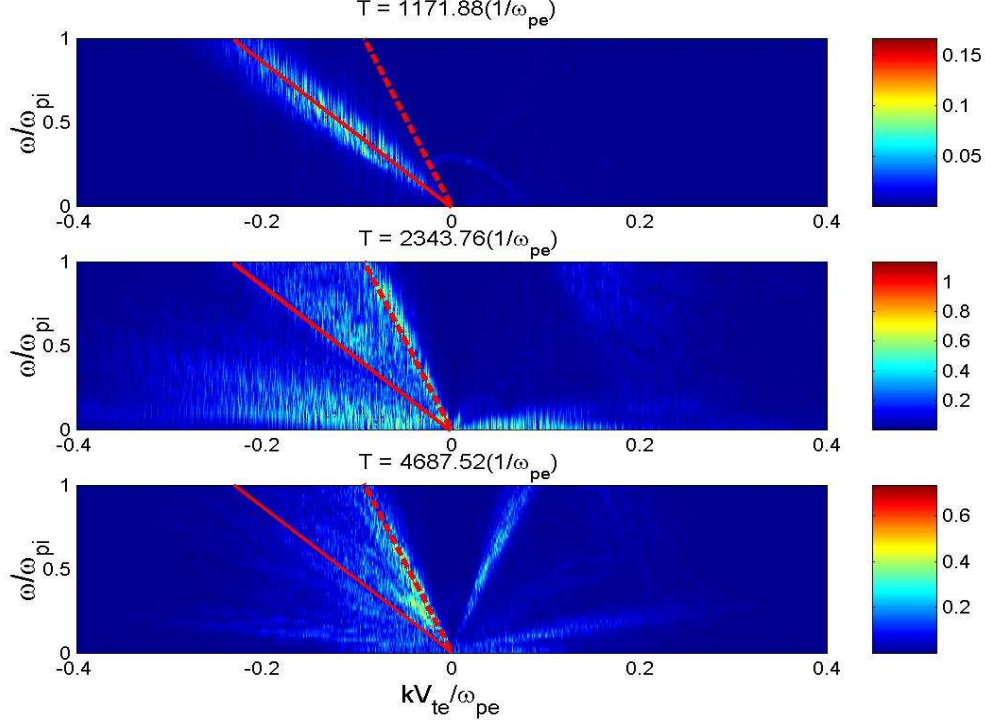
10

FIG. 4: The spectrum analysis of the generated electric field perturbations from the Vlasov simulation. The three panels correspond to wave spectra at different instants. The phase velocity of solid lines is $\omega/k = 0.01C$, the thermal velocity of return-current electrons. The dashed lines represent the phase velocity $\omega/k = 0.02C$, the initial drift of electron beam.

lowest values. The time of drift decreasing in Valsov simulation with same setup is around $T_{span} = 1000\omega_{pe}^{-1}$. The current relaxation takes place in the growing phase of instability and the localized electric field is amplified by the free energy support from bulk electron beams. A major different feature, comparing to the kinetic results in fig.3, shown in this panel is the current relaxation level at the late stage of simulation. In this multi-fluid simulation the electron drifts is eventually reduced to around $1/10$ of the original values, which is much smaller and indicates the existence of a stronger current dissipation mechanism in multi-fluid plasma description. Presumably the discrepancy is caused, whether it is physically complete, from the model simplification of real plasma condition in multi-fluid description.

Because a periodic boundary condition is applied, the energy is conserved and transformed from one kind to another at different stages, gradually. In the second panel of fig.5 the wave energy of perturbative electric field is shown as a function of time. In line with the electric field energy evolution, a good agreement is shown with the development of current relaxation trend. This indicates the degradation of electron bulk energy corresponds to the growth of field perturbative energy, i.e. energy is converted from bulk kinetic form to electric field perturbation.
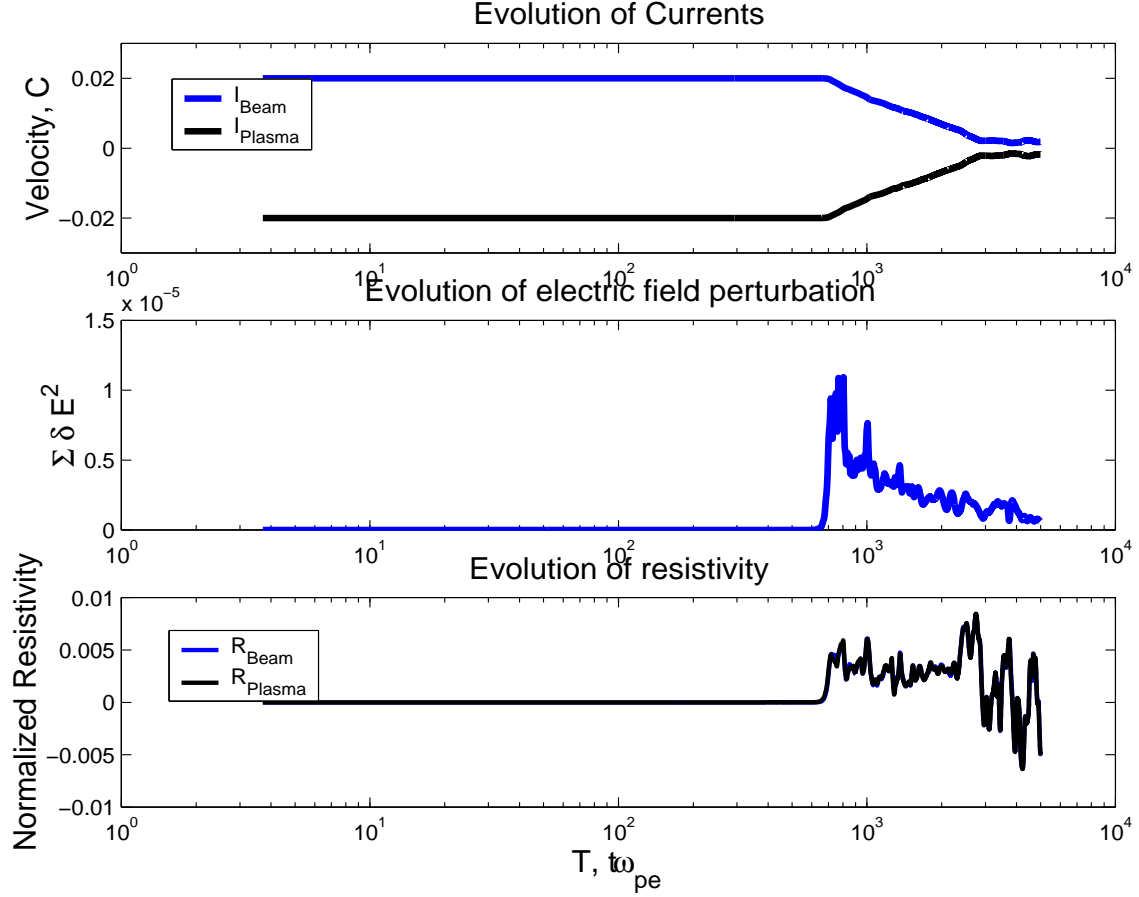
FIG. 5: The temporal evolutions of electron bulk motion, electric field perturbation and effective anomalous resistivities, defined as $R = (dm_j v_j / dt)/m_j v_j$. The final currents reduced to 1/10 of the original values, indicates a strong dissipation mechanism in multi-fluid plasma description.

In addition, the normalized temperatures of electron beams and ions increase along with the relaxation of bulk drifts, too. The temperatures of each species are shown in fig.6. The energy of electron bulk motions is dissipated and converted into electric field energy and hence the plasma thermal energy. It is also noticed that the heating efficiency of electrons is higher than the heating efficiency of ions. This is mainly because of the mass difference between electrons and ions, and the frequency of generated wave is closer to the Doppler-shifted electron plasma frequency.

The strongest anomalous resistivity (momentum transfer rate) appears when the electric field energy perturbation peaks in the system, showing the dissipation of currents is the result of local charge separation effect, which is the most influential dragging force in multi-fluid description. Note that particle-trapping can not be described in this multi-fluid system, but it is self-included in a kinetic system. The trapping effect is indeed an exhibition of Landau damping in phase space, i.e. those particles with close velocity as the Doppler-shifted phase velocity of large-amplitude plasma waves can interact and hence are trapped
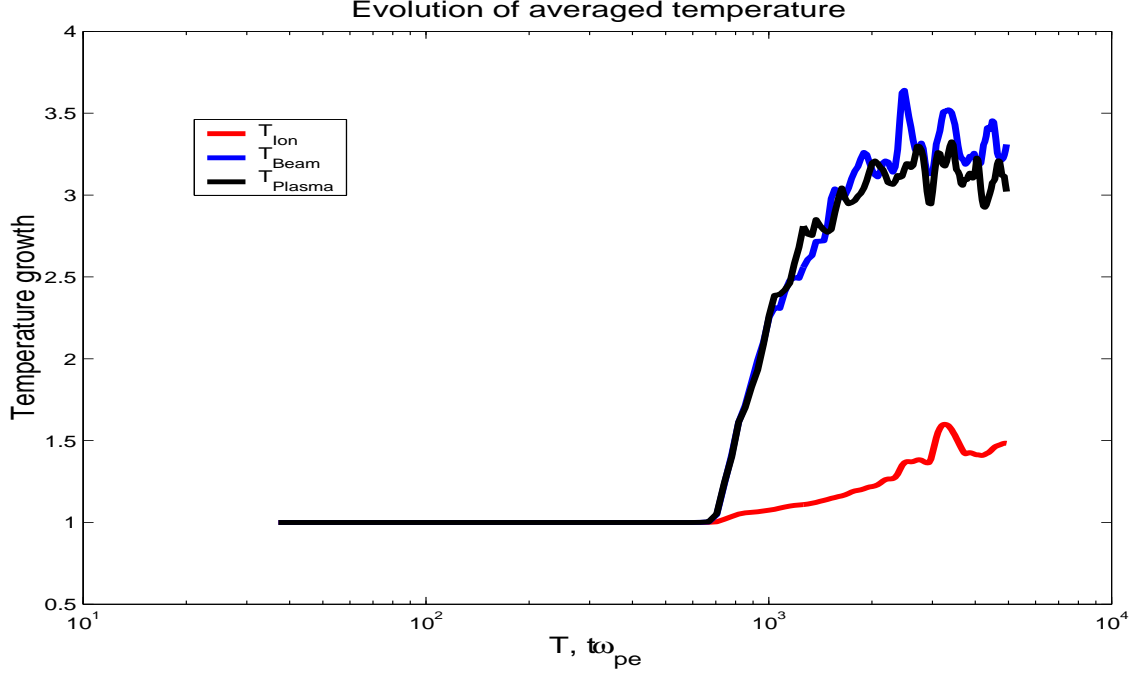
FIG. 6: The temperature history of beam electrons, return-current electrons background and ions, from multi-fluid simulation. Comparing with fig.5 it shows the temperature of both electron species increase along with the decrease of electron bulk velocities, i.e. it indicates the bulk kinetic energy is converted to electron thermal energy.

in the phase-space holes.

In fluid models, plasma species are all kept maxwellian distributions and the only kinetic information in phase space is their temperatures. In principle, a kinetic system can be described by infinite constitutions of maxwellian fluids. Hence it can make an analogy of phase space structures in multi-fluid system. In fig.7 the electron drifts and localized electric fields in the simulation domain are shown in phase-space plots, without the information of thermal expansion on the distributions. Initially the electrons drift uniformly in the domain, with an infinitesimal perterbations superposed onto the background. The initial perturbations stay small-amplitude for a period $T_{span} = 650\omega_{pe}^{-1}$ then an exponentially-growing phase follows. As one can see, from the left upper panel to the right lower panel in fig.7, the large-amplitude violent structures exist along with some synchronized trends on both beam and return-current electron drifts. In the view that a real phase-space hole in kinetic simulation is composed of distribution functions surrounding an empty space in the velocity space, for multi-fluid simulation the sychronized drifts can somewhat mimic the trend and put a circle inside certain domain, forming an analogy of phase-space structures. Also the dissipation of individual currents is seen in a form that the mean velocities of drifts decrease with time. The relaxation of bulk drifts therefore exhibits strong relation with the localized electric field structures, which are produced by charge-separation solely in the
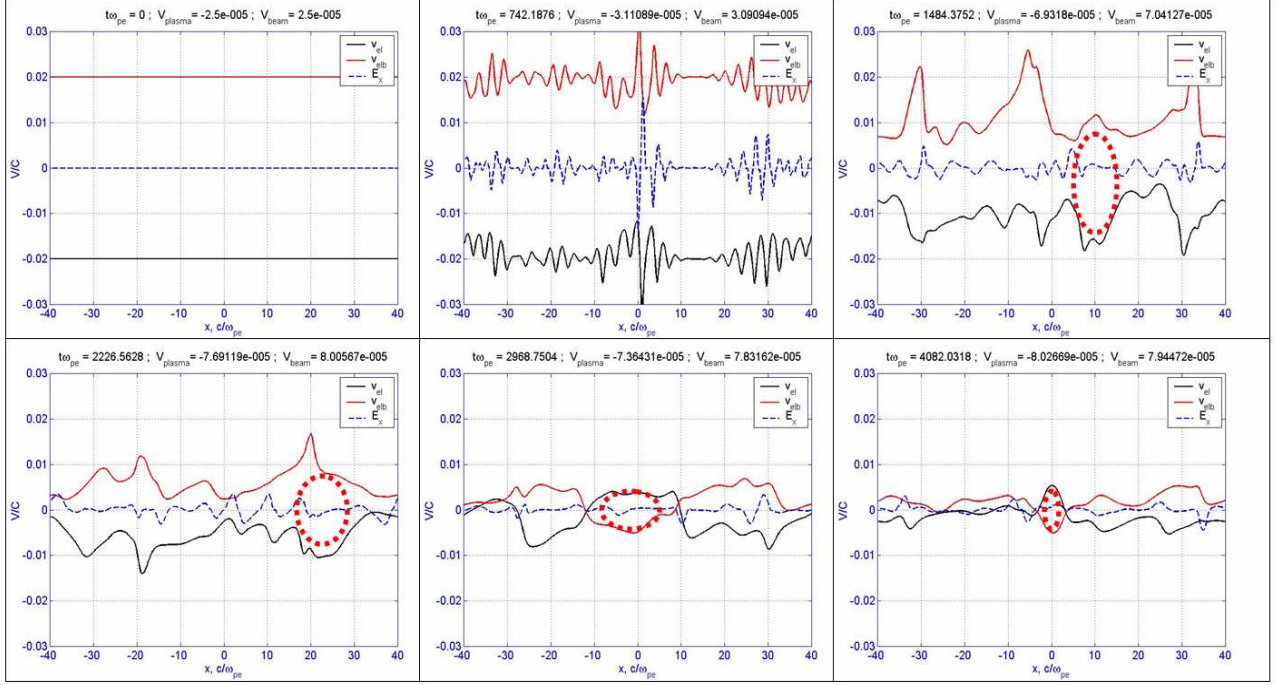
FIG. 7: The drift velocities of electron beams and the generated localized electric fields in simulation domain, at different time. The red-dashed circles indicate that the analogy of phase space stuctures located at certain positions in the domain. Comparing to Vlasov simulation, the trapping effects are excluded in multi-fluid plasma description.

electrostatic 1D multi-fluid simulation.

V.   LANDAU DAMPING AND SYSTEM STABILIZATION

Similar to the classical Joule heating caused by collisional momentum transfer, plasma is also heated in a collisionless system, though via a more complicated wave-particle interaction process instead of the binary collisions. Nevertheless, the anomalous transports which cause the energy conversion diversify in different plasma descriptions. In this section we would like to explore the mechanism that results into the effective transport discrepancy in kinetic and multi-fluid plasmas.

For the same plasma setups, it shows the current relaxation is stronger in multi-fluid description rather than in kinetic description. Look into the primary difference of these two regimes, the assumption of maxwellian distribution on each species distinguishes the multi-fluid regime from kinetic regime in the plasma evolution process. However this assumption does not sufficiently account for the stronger dissipation of currents in multi-fluid plasma. To look at the current relaxation time spent in both simulations, a longer relaxation process is observed in multi-fluid plasma before it comes to a stable state. At the initial stage of
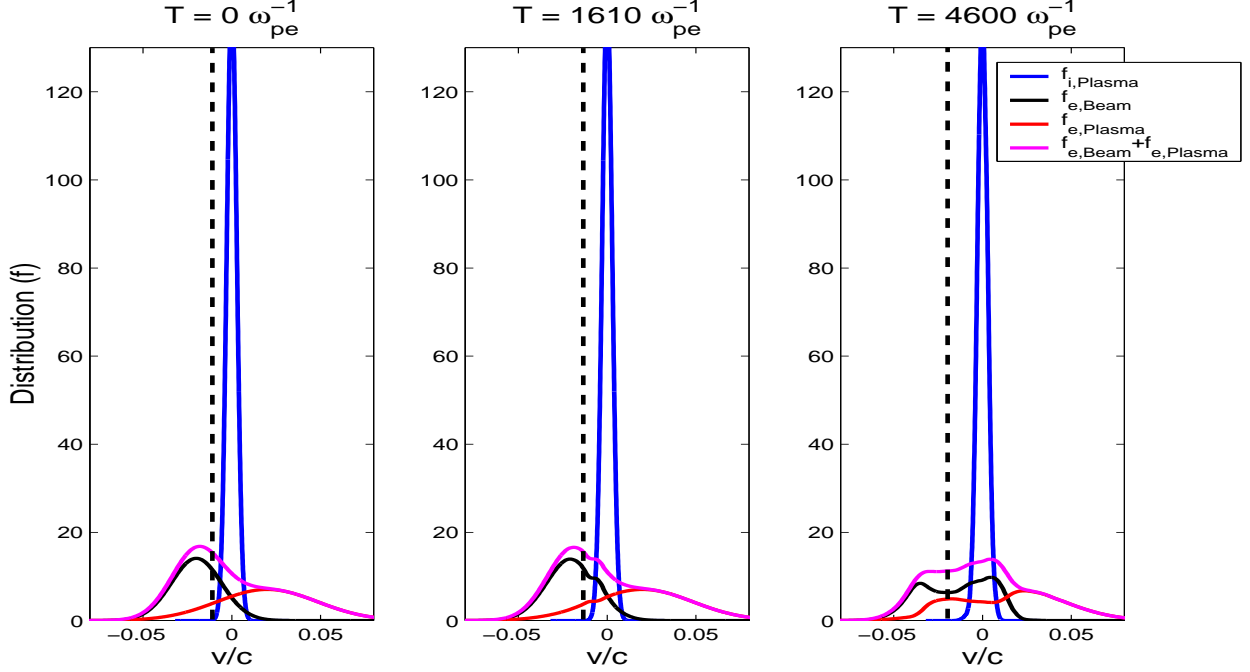
14

FIG. 8: The averaged distribution functions from Vlasov simulation at different instants. The vertical black dashed line indicates the phase velocity of strongest wave. Look at the Landau damping effect on electrons (magenta solid line and black dashed line), it shows the system is unstable at $T = 0\omega_{pe}^{-1}$ and $T = 1610\omega_{pe}^{-1}$, but the system is stabilized at $T = 4600\omega_{pe}^{-1}$.

evolution the electron drifts are high, hence the generated instabilities are more fluid-like in nature. Along with the development of instabilities the bulk drifts are slowed down, therefore the instability condition becomes more kinetic-like because the wave phase velocity drops in the electron thermal velocity range, for which the Landau damping effect comes into play. The question of the generation of different transport levels now centralize on the argument: Does the exclusion of Landau damping in multi-fluid regime result into the stronger current dissipation?

To verify the phypothesis, a combined spectrum analysis with an averaged distribution is used. This method excludes the individual interaction of local plasma with wave of a wide range of frequencies, instead, the global interaction of plasma majority with the primary wave mode is considered. In section III the primary wave modes are deduced in the simulation spectrum (in fig.4). The averaged distributions at different evolution stages, combined with the phase velocity of strongest wave mode, are plotted in fig.8. The distributions for ions, beam electrons, return-current electrons and whole electrons, are exhibited in blue, black, red and magenta lines. The first panel shows the distribution at $T = 0\omega_{pe}^{-1}$, the initial plasma setup. The initial phase velocity of wave deduced from spectrum, the Doppler-shifted electron plasma frequency, located in the distribution range with a nagative slope in the $f - v$ space, i.e. the black dashed line is in the negative slope of solid magenta line.
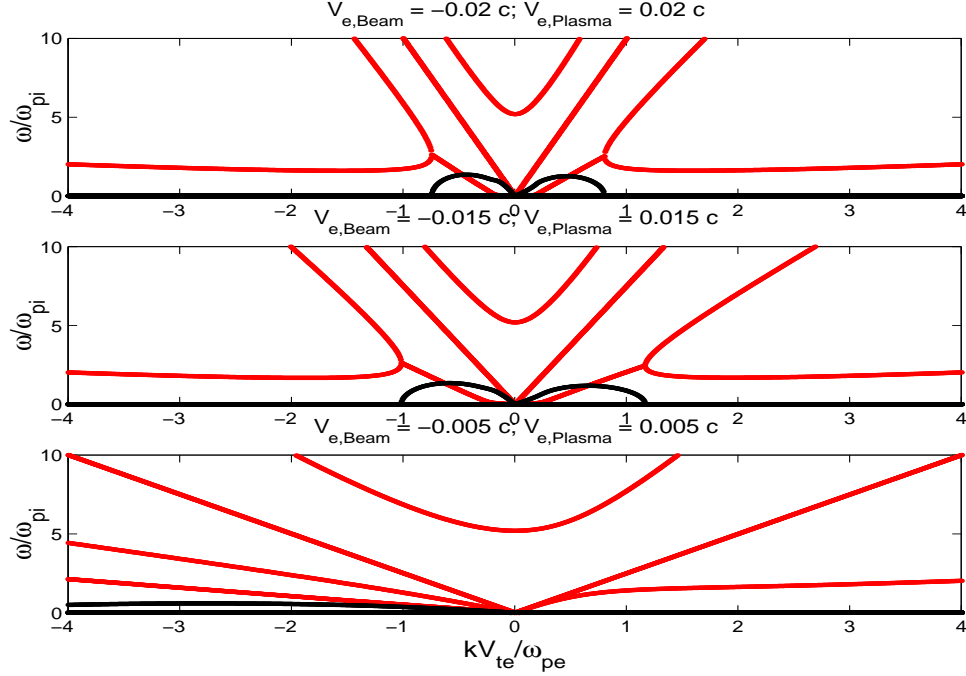
15

FIG. 9: The dispersion analysis of the plasma environment at different stages of multi-fluid sim-ulation. In this figure, it shows the growth rates (black solid lines) of instabilities exist even with very small drifts. This is a result of the exclusion of Landau correction in the large k (or small wave length) range.

More particles with higher velocity interact with the wave than particles with lower velocity, consequently the wave is amplified and indicates the existence of an instability.

Similar situation is shown in the second panel at $T = 1610\omega_{pe}^{-1}$, the beginning instant of current relaxation process. As shown in fig.4 the intensity of electric field in this stage is much stronger than in the initial. Electrostatic DLs start to appear at this stage as well as the fast electron holes, so there is a wider spread in the spectrum.

After the system went through a period of self-organization process, the whole electron distribution altered drastically (the magenta line in panel three of fig.8). Contrary to the stability condition at the initial stage, the particles with higher velocity are more or equal to the amount of particles with lower velocity, indicating a Landau-stable condition. Because the phase velocity of waves is getting larger, or in all case at least of the value of $|V_{ph}| \geq 0.01C$, the system becomes Landau-stable as long as the drift of electron beam reduced beneath this value. Approximately the bulk drifts drop from $|V| = 0.02C$ to $|V| \geq 0.01C$, and this explains the current relaxation is only roughly 3/4 of the initial value.

In contrast to the kinetic plasma, a multi-fluid plasma is governed by multi-fluid equa-tions. The Landau damping effect is not described in the multi-fluid regime, i.e. the dissi-pation of current always exists as long as the instability exist. In fig.9 the linear instability analysis is done for different drifts of electron beam, corresponding to the different drifts at

16

different stages of multi-fluid simulation. The red solid lines indicate the real frequencies of waves and black solid lines are the growth rates of unstable modes. It shows that the growth rates always exist even for a very small value of drift, indicating the plasma waves keep growing and extracting energy from the bulk energy of electron beams. This explains why the currents in the multi-fluid system can be reduced to a very small value.

Physically, the Landau damping effect becomes more and more significant when the physical process takes place in kinetic scale, i.e. large wave number k or small wave length λ. In our case, it means when the drifts become small then growth rates shift to the large k region, as shown in fig.9. Because the Landau damping is excluded in the linear analysis of multi-fluid plasma, as well as in the multi-fluid simulation, the dissipation took place in kinetic scale should be carefully treated.

VI.   DISCUSSION AND CONCLUSION

The generations of anomalous transports in a 1D electrostatic kinetic Vlasov plasma and in a 1D electrostatic three-fluid plasma are studied via numerical simulations. Different transport levels were observed, though the simulation setups are the same for two different models. With the recognition that the Vlasov description is the more detailed, closer to physical reality description than multi-fluid model, an estimation of anomalous transport levels in two models is given. A combined spectrum analysis is provided in this work to explain the physical process and the generated difference of anomalous transport levels.

The advantage of a multi-fluid model over a fully kinetic model like given by the Vlasov equation is the chance to consider larger systems and complicated geometries, inclduing 2- and 3-dimensional ones. For a complete description and applications the irreversibily due to Landau damping can be introduced via an appropriate term, hence this study provides an estimation on setting the anomalous transport intensity in multi-fluid model.

As previous literatures reported, electrostatic DLs appear in kinetic Vlasov simulation as energy converters that dissipate bulk kinetic energy of electron beams and heat the plasma in the late stage of evolution. Spectrum analysis of the plasma waves shows the phase velocities increase from the initial thermal velocity of return current electrons $|V_{thermal}| = 0.01C$ to a value close to the initial drift velocity $|V_{drift,RC}| = 0.02C$.

For the results from multi-fluid simulation, current relaxation and plasma heating are also observed, indicating that a mechanism comes into play as energy converter, and in 1D electrostatic multi-fluid plasma it's the charge separation effects. The major different feature shown in multi-fluid plasma, comparing to kinetic Vlasov plasma, is the current relaxation level is much stronger than that in kinetic plasma. From the physical model we assumed this discrepancy of transport levels comes primarily from the neglect of Landau damping in the multi-fluid regime.

To verify the assumption the Landau damping plays a major role that results the dif-

ference, we analyzed the averaged distributions from kinetic Valsov simulation at different stages. It shows the Landau damping stabilized the current relaxation when the bulk drifts drop just beneath the phase velocity of waves. Because the phase velocity increases from the initial thermal velocity of return current electrons and its value is not small, the current reduction is not severe and is around 3/4 of the initial value.

For multi-fluid plasma of the same initial setup, the linear dispersion analysis as well as the numerical scheme are described without Landau effect. The instability and its growth rate exist even for a very small drift, hence the waves keep extracting energy from the electron bulk motions, causing the drastic reduction of drifts. As shown in the simulation results, the bulk drifts in the final stage drop to 1/10 of the initial values. Comparing to the fully kinetic Vlasov results, the ability of current relaxation in a multi-fluid description is around 3.5 times stronger, for specific velocity ratios.

The case we considered in this work is a 1D electrostatic case, which represents the fact that localized electrostatic structures have a dominant role in generation of anomalous resistivity, which has been reported in many literatures. However, in a real multi-dimensional electromagnetic plasma different modes may come into play significant roles as well. Since the multi-fluid description of plasma has been widely considered and used in many space and astrophysical study, to obtain a precise scenario of plasma evolution in these transient and energetic events, a more careful and detailed study of the anomalous transport in this multi-fluid regime should be studied and treated more carefully.

Acknowledgments

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